Polarization-independent metal-dielectric grating with improved bandwidth

Bo Wang[*], Hongtao Li, Wenhao Shu, Wenhua Li, Li Chen, Liang Lei, Jinyun Zhou

School of Physics and Optoelectronic Engineering, Guangdong University of Technology, Guangzhou 510006, China

[*]Corresponding author: wangb_wsx@yeah.net

A polarization-independent reflective grating with improved bandwidth is presented based on the mixed metal-dielectric grating. The novel grating is composed of the substrate, the metal slab, two dielectric layers, and the covering layer. The grating parameters are optimized for the special duty cycle of 0.6 at an incident wavelength of 1550 nm used in dense wavelength division multiplexing (DWDM). With the designed grating, high efficiency can be diffracted into the reflective −1st order for both TE and TM polarizations, where the polarization-independence is exhibited. Most importantly, the efficiency of more than 90% can be achieved within the incident wavelength bandwidth of 1262–1686 nm, where the bandwidth is improved greatly compared with the reported surface-relief single-layer grating. The reflective grating can have advantages of high efficiency, polarization-independence, and wide bandwidth, which should be useful for DWDM applications.

Keywords: rigorous coupled-wave analysis, reflective efficiency, improved bandwidth.

1. Introduction

Diffraction gratings can be novel micro-optical elements when the periods approach the incident wavelength [1–5]. For such high-density gratings, novel optical properties can be exhibited, such as high efficiency, polarization, and so on. The progress in microphotolithography and inductively coupled plasma dry etching can make it possible to produce diffractive grating elements with smaller features [6–8]. Therefore, high-density gratings attract more and more attention in the aspect of miniaturization in the resonance domain [9–11], which can be expected to realize special functions based on their distinctive profiles. Among them, high efficiency can be useful for dense wavelength division multiplexing (DWDM) [12]. Current DWDM technology can be realized by thin-film filters, arrayed waveguide gratings, fiber Bragg gratings, and free-space diffraction gratings. It is interesting that free-space gratings have many advantages: parallel demultiplexing, stable performance, and low polarization-dependent losses.

A single-layer surface-relief grating has been designed at a wavelength of 1550 nm with the transmissive structure [13]. With the optimized grating parameters, by using rigorous coupled-wave analysis (RCWA) [14], efficiencies more than 95% and 80% can be reached for TE and TM polarizations, respectively. Although the validity has been demonstrated in experiments, the efficiency needs to be further enhanced. Moreover, considering the bandwidth, efficiency above 90% can be kept for the C+L band with a wavelength from 1460 to 1620 nm for TE polarization. However, for TM polarization, efficiency can be kept above only 70%. It is desirable to design a novel grating with high efficiency and wide bandwidth for both TE and TM polarizations. To our knowledge, no one has presented the reflective sandwiched two-layer grating at the wavelength of 1550 nm with improved bandwidth for DWDM applications.

In this paper, a polarization-independent reflective grating with improved bandwidth is presented for the new grating configuration. The high efficiency can be realized by the sandwiched structure. And the bandwidth can be improved with the two-layer grating. Such a reflective grating includes mixed metal-dielectric layers. The proposed novel metal-based grating can reflect the incident light for the special duty cycle of 0.6 with polarization-independence and improved bandwidth.

2. Polarization-independent reflective sandwiched grating

As shown in Fig. 1, the polarization-independent reflective grating with improved bandwidth has the mixed metal-dielectric structure. From the bottom to the top, the grating is composed of the substrate of fused silica, the Ag slab with the depth of $h_m = 100$ nm and the refractive index $n_m = 0.469 - 9.32i$, the first grating layer of Ta_2O_5 with the depth of h_1 and the refractive index $n_1 = 2$, the second layer of fused silica with the depth of h_2 and the refractive index $n_2 = 1.45$, and covering layer of fused silica. TE polarization (electric filed perpendicular to the plane of incidence) or TM polarization (magnetic filed perpendicular to the plane of incidence) with wavelength of λ is incident upon the grating with period of d at the Bragg angle of $\theta_i = \sin^{-1}[\lambda/(2n_2 d)]$, which can
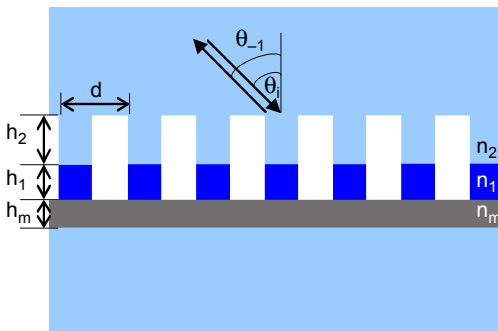

Fig. 1. Schematic picture of a polarization-independent reflective sandwiched grating with high efficiency.

be called the Littrow mounting. The mixed metal-dielectric grating can be operated with high efficiency in the reflective −1st order with the Ag slab coated on the substrate.

The novel grating has the mixed metal-dielectric structure, which has many parameters to be optimized: duty cycle, period, and depths of two layers. It has the potential to optimize those parameters to achieve good performance. RCWA can be widely used to analyze the diffraction for dielectric and/or metallic gratings. Therefore, the efficiency can be simulated with various grating parameters by using RCWA. Figure 2 shows efficiency in the −1st order of a reflective sandwiched grating *versus* grating depths at the incident wavelength of 1550 nm under the Littrow mounting for both TE and TM polarizations, where the grating duty cycle is 0.6 and period is 1100 nm. One can see that the mixed metal-dielectric grating can diffract TE polarization with the efficiency of 96.44% and TM polarization with the efficiency of 96.25% into the −1st order with depths of $h_1 = 0.45$ µm and $h_2 = 0.75$ µm. From the optimized results, the reflective sandwiched two-layer grating can exhibit higher efficiency than the reported transmissive surface-relief single-layer grating with efficiencies above 95% for TE polarization and 80% for TM polarization [13].
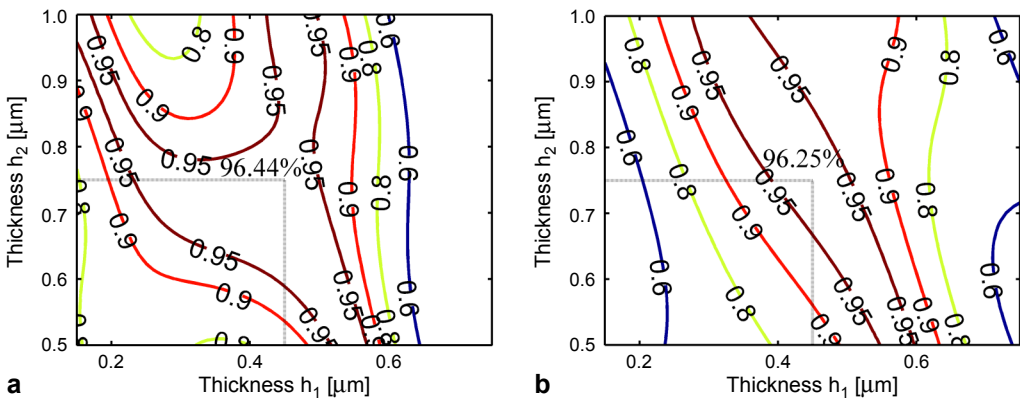

Fig. 2. Efficiency in the −1st order of a reflective sandwiched grating *versus* grating depths at the incident wavelength of 1550 nm under Littrow mounting: TE polarization (**a**) and TM polarization (**b**).

Furthermore, it is necessary to investigate the fabrication tolerance considering less control of etching conditions. The grating depths can affect the efficiency of both diffracted orders with the variation from the optimized results. Efficiencies more than 95% can still be exhibited with the depths range of 0.43 µm < h_1 < 0.47 µm and 0.70 µm < h_2 < 0.82 µm. Therefore, it is possible to fabricate such a polarization-independent reflective grating with high efficiency. During forming the grating mask and etching in the dielectric layer, the duty cycle may change from the special given value of 0.6. Many grating-based elements are sensitive to the duty cycle variation. Figure 3 shows reflective efficiency of a sandwiched grating *versus* a duty cycle with optimized
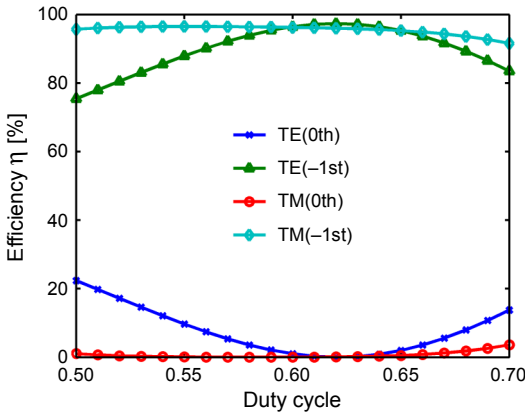
Fig. 3. Reflective efficiency of a sandwiched grating *versus* duty cycle with optimized grating depths.

grating depths. In Figure 3, within the duty cycle tolerance of 0.59–0.65, the mixed metal-dielectric grating can diffract both TE and TM polarizations with efficiency more than 95%. Considering the fabrication tolerance, the reflective grating can exhibit high efficiency with a polarization-independent property for not only the special designed values but also the given tolerance.

3. High efficiency with wide bandwidth

For DWDM technology, the bandwidth of a fiber can be enlarged enormously. Although many gratings are optimized at a wavelength of 1550 nm for DWDM, some grating-based elements suffer from the narrow bandwidth. It has been reported that the two-layer grating can exhibit wide bandwidth compared with the single-layer grating [15]. The reported two-layer gratings are mostly based on the transmission struc-
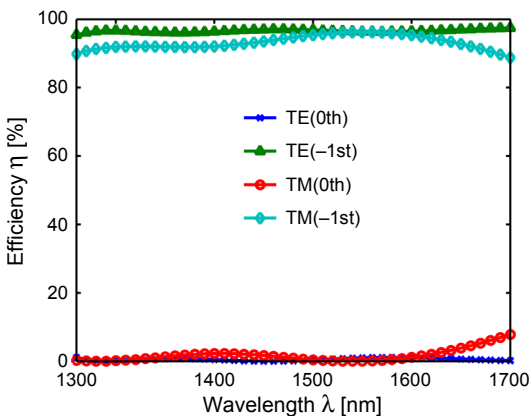

Fig. 4. Reflective efficiency *versus* incident wavelength for the optimized sandwiched grating with wide bandwidth under Littrow mounting.

ture. Such a two-layer grating can also be operated in the reflection by the mixed metal-dielectric configuration.

Figure 4 shows reflective efficiency *versus* incident wavelength for the optimized sandwiched grating with wide bandwidth under the Littrow mounting. For thin-film filters, high losses can be shown with an increasing number of channels. For the free--space diffraction grating in this paper, efficiency more than 90% can be exhibited within the incident wavelength bandwidth of 1262–1686 nm for both TE and TM polarizations. The bandwidth is improved greatly compared with wavelength bandwidth of 1460–1620 nm for TE polarization with efficiency more than 90% [13]. Most importantly, the transmission efficiency can be kept above only 70% within the given wavelength bandwidth of 1460–1620 nm for the surface-relief single-layer grating [13]. For the comparison with the single-layer grating, Table 1 shows the grating efficiency and incident bandwidth for different grating types. Polarization-independent with improved bandwidth can be achieved by the mixed metal-dielectric grating.

T a b l e 1. Grating efficiency and incident bandwidth for different grating types.

Grating type	Efficiency	Wavelength bandwidth
Surface-relief single-layer grating [13]	TE: ≥95%	1460–1620 nm
	TM: ≥80%	TE: $\eta \geq 90\%$, TM: $\eta \geq 70\%$
Sandwiched two-layer grating in reflection	TE: 96.44%	1262–1686 nm
	TM: 96.25%	TE/TM: $\eta \geq 90\%$

The mixed metal-dielectric grating is designed at the Bragg angle to achieve high efficiency. With deviation of the incident angle, the efficiency may usually change to some extent. Figure 5 shows the reflective efficiency *versus* the incident angle at the incident wavelength of 1550 nm for the optimized sandwiched grating. However, efficiency more than 90% can be exhibited within the incident angular range of
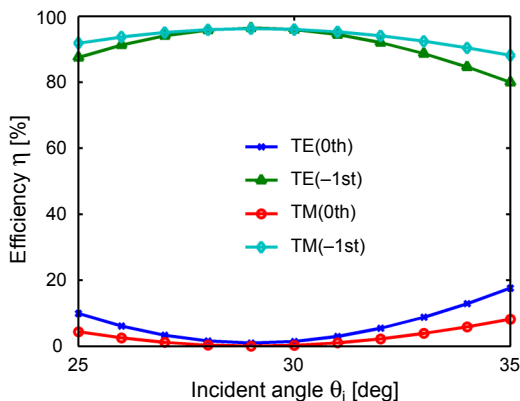

Fig. 5. Reflective efficiency *versus* incident angle at the incident wavelength of 1550 nm for the optimized sandwiched grating.

25.7–32.6 deg for both TE and TM polarizations. The polarization-independent losses can be reduced compared with not only arrayed waveguide grating but also the surface--relief single-layer grating [13].

4. Conclusion

In conclusion, a polarization-independent reflective grating with improved bandwidth is presented based on the mixed metal-dielectric grating. The grating parameters are optimized for the special duty cycle of 0.6. Efficiencies of 96.44% for TE polarization and 96.25% for TM polarization can be exhibited in the –1st order. The polarization-independent property can be achieved with high efficiency by the reflective sandwiched grating. Moreover, for different incident wavelengths, efficiency more than 90% can be diffracted within the wavelength bandwidth of 1262–1686 nm for both TE and TM polarizations. The incident bandwidth is greatly improved compared with the surface-relief single-layer grating [13], especially for TM polarization. Since the DWDM technology has been designed and demonstrated based on the two-layer grating [15], the proposed reflective mixed metal-dielectric grating is potential to be fabricated and applied in DWDM with advantages of high efficiency, polarization-independence, and wide bandwidth.

References

[1] Xufeng Jing, Shangzhong Jin, Ying Tian, Pei Liang, Qianmin Dong, Le Wang, *Analysis of the sinusoidal nanopatterning grating structure*, Optics and Laser Technology **48**, 2013, pp. 160–166.

[2] Sen Jia, Lihe Yan, Jinhai Si, Wenhui Yi, Feng Chen, Xun Hou, *Subwavelength beam focusing by multiple-metal slits surrounded by chirped dielectric surface gratings*, Optics Communications **285**(6), 2012, pp. 1519–1522.

[3] Chenying Yang, Weidong Shen, Yueguang Zhang, Ding Zhao, Xu Liu, *Multi-narrowband absorber based on subwavelength grating structure*, Optics Communications **331**, 2014, pp. 310–315.

[4] Ansbaek T., Il-Sug Chung, Semenova E.S., Yvind K., *1060-nm tunable monolithic high index contrast subwavelength grating VCSEL*, IEEE Photonics Technology Letters **25**(4), 2013, pp. 365–367.

[5] Saastamoinen T., Lajunen H., *Increase of spatial coherence by subwavelength metallic gratings*, Optics Letters **38**(23), 2013, pp. 5000–5003.

[6] Kanamori Y., Okochi M., Hane K., *Fabrication of antireflection subwavelength gratings at the tips of optical fibers using UV nanoimprint lithography*, Optics Express **21**(1), 2013, pp. 322–328.

[7] Arriola A., Rodriguez A., Perez N., Tavera T., Withford M.J., Fuerbach A., Olaizola S.M., *Fabrication of high quality sub-micron Au gratings over large areas with pulsed laser interference lithography for SPR sensors*, Optical Materials Express **2**(11), 2012, pp. 1571–1579.

[8] Bin Yu, Wei Jia, Changhe Zhou, Hongchao Cao, Wenting Sun, *Grating imaging scanning lithography*, Chinese Optics Letters **11**(8), 2013, article 080501.

[9] Jijun Feng, Changhe Zhou, Jiangjun Zheng, Hongchao Cao, Peng Lv, *Design and fabrication of a polarization-independent two-port beam splitter*, Applied Optics **48**(29), 2009, pp. 5636–5641.

[10] Bo Wang, Li Chen, Liang Lei, Jinyun Zhou, *Two-layer dielectric grating as two-port beam splitter*, IEEE Photonics Technology Letters **25**(9), 2013, pp. 863–866.

[11] Lochbihler H., Yan Ye, *Two-dimensional subwavelength gratings with different frontside/backside reflectance*, Optics Letters **38**(7), 2013, pp. 1028–1030.

[12] Yanyan Zhang, Changhe Zhou, *High-efficiency reflective diffraction gratings in fused silica as (de)multiplexers at 1.55 µm for dense wavelength division multiplexing application*, Journal of the Optical Society of America A **22**(2), 2005, pp. 331–334.

[13] Shunquan Wang, Changhe Zhou, Yanyan Zhang, Huayi Ru, *Deep-etched high-density fused-silica transmission gratings with high efficiency at a wavelength of 1550 nm*, Applied Optics **45**(12), 2006, pp. 2567–2571.

[14] Moharam M.G., Gaylord T.K., Pommet D.A., Grann E.B., *Stable implementation of the rigorous coupled-wave analysis for surface-relief gratings: enhanced transmittance matrix approach*, Journal of the Optical Society of America A **12**(5), 1995, pp. 1077–1086.

[15] Shiozaki M., Shigehara M., *Novel design of polarization independent multi-layer diffraction grating with high angular dispersion*, SEI Technical Review **59**, 2005, pp. 27–31.